Weed Science. 1986. Volume 34:676–684

Uptake and Translocation of ^{14}C-Fluazifop by Quackgrass (*Agropyron repens*)[1]

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Abstract. **Detached leaves and whole plants of quackgrass [*Agropyron repens* (L.) Beauv. #[3] AGRRE] were used to study uptake and translocation of butyl esters of ^{14}C-fluazifop {(±)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl] oxy] phenoxy] propanoic acid}, with or without additional adjuvants. In the absence of adjuvants 3.2% of applied radioactivity entered detached quackgrass leaves by 6 h, and at the end of 24 h, 6.0% had penetrated. The presence of additives increased uptake by leaves significantly. In the presence of the non-ionic surfactant Agral (nonyl phenol ethoxylate) at 0.2% (v/v) or the oil-additive Actipron (self-emulsifying adjuvant oil) at 2.0% (v/v), 17.2 and 12.9% of applied radioactivity, respectively, entered the leaves by 24 h. Evidence of dependence of phloem translocation of the radioactivity on source-sink relationships of the plant was obtained in the studies with whole plants. Translocation measured up to 7 days after treatment showed that radioactivity was concentrated in areas such as young developed leaves, young stems, and rhizome apices. Rhizomes appear to be major sinks for the accumulation of radioactivity and at 7 days 0.5% of applied radioactivity was found there. In whole-plant experiments the two adjuvants either individually or in mixture increased the uptake of ^{14}C-fluazifop significantly. However, a corresponding increase in basipetal translocation was found only in one experiment. Much of the increased activity that had entered the leaves in the presence of adjuvants was found to have moved to areas distal to the treated zone or remained within the treated zones. In all experiments, applied ^{14}C was not fully recovered. Evidence of significant volatility losses from treated surfaces was obtained and it is thought that this may be the main reason for the inability to recover all of the applied activity.**

Additional index words. **Absorption, translocation, adjuvants, surfactants, oil additives, *Agropyron repens*, AGRRE.**

INTRODUCTION

The efficiency of a phytotoxic foliar-applied herbicide for the control of a perennial grass weed such as quackgrass is mainly related to the amount absorbed by the treated plants, the amount translocated out of leaves, and the amount that reaches the subterranean, regenerative parts. Fluazifop, a systemic postemergence herbicide, has been shown to be highly effective in the selective control of perennial grasses such as quackgrass and many annual grasses in broadleaf crops (4, 8, 11, 16). At low doses (0.125 and 0.25 kg ai/ha), translocation of fluazifop to the rhizomes of quackgrass occurred mainly between 6 and 48 h after application (4). When the herbicide was sprayed at a dose range of 0.125 to 1.0 kg ai/ha, at least 90% of the buds had accumulated a lethal dose within 72 h of spraying (4). It has been recently shown that differential absorption and translocation did not contribute to the selectivity of fluazifop between quackgrass and soybean [*Glycine max* (L.) Merr.] (10).

Often surfactants and oil additives are incorporated into sprays to increase the performance of foliar-applied herbicides. Surfactants may lower the surface tension of the spray solution with a resultant increase in leaf wetting and retention, both of which may assist herbicide uptake. Oils may aid penetration by being more efficient carriers, by decreasing the rate of drying of droplets, and by generally improving the wetting and spreading properties of the spray solution. There is much evidence in the literature to show that such adjuvants do improve penetration (1, 6, 13, 14, 21). However, as Norris (15) pointed out there is little detailed evidence of the role of adjuvants in herbicide translocation in plants. Instances of increased herbicide absorption and associated increases in movement in the presence of additives have been reported (9, 13, 17). However, other workers (14) have reported that the presence of surfactants and other adjuvants actually reduced the translocation of herbicides from treated areas, despite increased overall toxicity.

The objectives of this research were to examine: a) the uptake and translocation of ^{14}C-fluazifop in quackgrass as a function of time, b) the accumulation of the herbicide in quackgrass rhizomes, and c) the effect of a surfactant (Agral)[4] and an oil additive (Actipron)[5] on both uptake and translocation of ^{14}C-fluazifop.

MATERIALS AND METHODS

Growth of plants. Rhizomes of quackgrass obtained from a clone maintained at the Penyffridd Field Station of the University College of North Wales in Bangor, Gwynedd, U.K., were cut into single-node pieces, 25 to 30 mm long and planted in flat trays (42 by 30 by 4 cm) containing washed quarry sand. They were covered with 1 cm of potting soil (1:1:1, soil:sand:peat) and placed in a heated glasshouse where the temperature varied between 18 and 22 C and the relative humidity was 60 to 65%. Natural daylight was supplemented with 400-watt mercury vapor lamps providing a 16-h illumination of 250 $\mu E \cdot m^{-2} \cdot s^{-1}$ PPFD. When new plants had emerged and grown for about 14 days, they were transplanted singly into 9.5-cm-diam plastic pots filled with potting soil. Plants received adequate water to maintain

[1] Received for publication February 21, 1985, and in revised form February 27, 1986.

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[3] Letters following this symbol are a WSSA-approved computer code from Composite List of Weeds, Weed Sci. 32, Suppl. 2. Available from WSSA, 309 West Clark Street, Champaign, IL 61820.

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soil moisture at or near field capacity and were grown for several weeks after transplanting.

Preparation of ^{14}C-treatment solution. The butyl ester of ^{14}C-fluazifop, labeled at the ester carbonyl atom and having a specific activity of 21.5 mCi/mmol, was used. An emulsifiable concentrate equivalent to commercial fluazifop (250 μg/μl) but containing radiolabeled fluazifop was prepared by adding the appropriate volumes of a blank formulation[6] and 100% technical grade fluazifop. Depending on the number of treatments, replicate leaves, or plants to be treated and treatment volumes per leaf or plant, the required volume of emulsifiable concentrate was prepared and diluted in deionized water to an emulsion containing 9 nCi/μl (for detached-leaf experiments) or 0.1 μCi/μl (for whole-plant experiments). The final herbicide concentration was adjusted to 5.0 μg fluazifop per μl.

Detached-leaf experiments. Quackgrass plants for detached-leaf experiments were 6 to 7 weeks old after transplanting and had six to eight leaves on the main shoot. Uniform groups of plants were brought to the laboratory on the day of each experiment. The third youngest, fully expanded leaf from each plant was detached under water and placed across the edge of a 5.5-cm-diam plastic petri dish, one leaf per dish, with the base of the lamina resting in 20 ml of deionized water. The adaxial surface was up and each leaf was held in place by a small piece of sticky cloth tape attached to the rim of the dish and the underside of the leaf.

In one experiment, where the time-course of uptake of ^{14}C-fluazifop by detached leaves of quackgrass was studied, each leaf was treated with 0.0225 μCi and absorption measured after 1, 3, 6, 12, and 24 h. No additional adjuvant was incorporated in the treatment solution in this experiment. In a second experiment, which investigated the influence of adjuvants on the uptake of ^{14}C fluazifop, detached leaves were treated with ^{14}C-fluazifop (0.0225 μCi) alone or plus surfactant Agral at 0.05, 0.1, or 0.2% (v/v), or the oil additive Actipron at 0.5, 1.0, or 2.0% (v/v). Absorption was measured after 6 and 24 h. A 1.0-μl microsyringe was used to apply five 0.5-μl droplets of the radiolabel in a row close to the midvein on the adaxial surface, 3 to 10 cm from the ligule of the leaf. Applications were done in the laboratory (23 C). Immediately afterwards the petri dishes were transferred to a growth cabinet operating at 21 ± 1 C, 75 to 80% relative humidity. The growth cabinet was illuminated by several rows of daylight fluorescent lamps which supplied a radiant flux density of 80.0 $W \cdot m^{-2}$ (PAR). In both experiments there were four replicate leaves per treatment and within the growth cabinet the petri dishes were completely randomized.

Whole-plant experiments. Quackgrass plants for whole-plant experiments were 12 to 13 weeks old after transplanting and had, on average, 7 to 9 leaves on the main shoot, and 3 to 4 well-developed tillers. Average height of plants was approximately 120 cm measured from the base of the plant to the tip of the youngest unfolding leaf. The plants also had well-developed rhizome systems. At the beginning of each experiment, plants were selected for uniformity.

Immediately prior to application of radiolabeled herbicide, plants were sprayed with 0.5 kg ai/ha of unlabeled fluazifop in combination with 0.1% (v/v) of Agral, using an Oxford Precision Sprayer[7] fitted with an Allman No. 0[8] nozzle at a pressure of 2.25 kg/cm^2. During this spraying, the second youngest leaf (to be treated later) was kept covered by careful insertion of the leaf into a lightweight polyethylene envelope just wide enough to accomodate it. After the spraying the leaves to be treated were uncovered, placed horizontally on a movable stage, and held with small strips of sticky cloth tape. Using the 1.0-μl microsyringe, ten 0.5-μl droplets of the radiolabel were placed in a row close to the midvein, on the adaxial surface between 5 and 15 cm from the ligule. Absorption and translocation studies with whole plants and ^{14}C-fluazifop were replicated five times. All radioactive treatments were made inside the glasshouse where the temperature was approximately 22 C, relative humidity 60%, and the light intensity 250 $\mu E \cdot m^{-2} \cdot s^{-1}$. Except in the time-course experiment, plants were harvested 3 days after radioactive applications.

Time-course of uptake and translocation. Quackgrass plants were treated with 0.5 μCi/plant of radioactivity using a treatment solution containing 0.1 μCi/μl of ^{14}C-fluazifop. No additional adjuvant was used in this experiment. Plants were harvested 12, 24, 48, 72, and 168 h after treatment.

Effect of adjuvants on uptake and translocation. In this experiment, each plant received 0.25 μCi of ^{14}C-fluazifop with or without either 0.1 or 0.2% (v/v) Agral or 1.0 or 2.0% (v/v) Actipron. Each treatment solution contained 0.05 μCi/μl of radioactivity.

Effect of adjuvant mixtures on uptake and translocation. The treatment solutions in this experiment were fluazifop-butyl alone, or with adjuvant mixtures containing 0.1 or 0.2% (v/v) Agral and 1.0 or 2.0% (v/v) Actipron in all combinations. Each plant received 0.25 μCi of ^{14}C from a treatment solution that had 0.05 μCi/μl of ^{14}C-fluazifop with or without adjuvants.

Plant harvesting and ^{14}C-assay. In detached-leaf experiments, at each harvest, leaves were removed from dishes and the unabsorbed ^{14}C-residue was rinsed with three 5-ml aliquots of deionized water (water rinse), followed by dipping the treated zone for 5 s in 10 ml of n-hexane (hexane rinse). The water remaining in the petri dishes was collected separately. All liquid samples were radioassayed by adding 1-ml aliquots into 10 ml of a dioxane-based scintillant[9]. The leaves were freeze-dried for 24 h, stored in paper bags, and later oxidized in a biological sample oxidizer[10]. The $^{14}CO_2$ liberated was collected in 15 ml of a scintillant cocktail

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[7] MDM Engineering (Portsmouth), Ltd., 34 Aston Rd., Waterlooville, Hampshire, England.

[8] E. Allman & Co., Ltd., Birdham Rd., Chichester, Sussex, England.

[9] Dioxane-based liquid scintillator fluid (NE 250) supplied by Nuclear Enterprises, Ltd., Sighthill, Edinburgh EH11 4EY, Scotland, U.K.

[10] Harvey biological material oxidizer model OX 100, R. J. Harvey Instruments Corp., 123 Patterson Street, Hillsdale, NJ 07642, U.S.A.

containing a CO_2 absorbent[11] and radioassayed using liquid scintillation spectrometry.

In the whole-plant experiments, plants were separated into leaves and stems above treated leaf, leaves and stems below treated leaf, treated leaf, roots, rhizomes, and tillers. The treated leaf was divided into area above treated zone, area below treated zone, and the treated zone itself. The unabsorbed ^{14}C-residue on the treated zone was washed as described previously and the rinses collected. The various plant parts were freeze-dried for 24 h and later assayed after oxidizing as described above. Where necessary, large plant parts were ground after drying and 50- to 100-mg subsamples used for radioassay.

A more detailed quantitative analysis of the ^{14}C-activity in the rhizomes was carried out with three replicates from each harvest time from the time-course experiment. For this purpose all rhizomes that exceeded 10 cm in length were sectioned into an apical 5.0-cm-long portion, a basal 5.0-cm portion, and a middle piece of varying length (1.0 to 21.0 cm). The activity in each piece was assayed separately.

Loss of ^{14}C-fluazifop from a glass surface in the laboratory. To investigate the volatility of the herbicide, thin glass cover slips (1.5-cm-diam) held on glass slides with sticky tape were treated with 1-μl droplets of ^{14}C-fluazifop formulated in the same way as previously described. One-μl samples were transferred directly into each of five counting vials containing 14 ml of the dioxane-based scintillant for determination of initial activity. There were five replicate cover slips per harvest time and these were placed under a laboratory light bank having a radiant flux density of 80.0 W·m^2 (PAR) supplied by several mercury vapor lamps. The temperature in the laboratory was 22 C and the relative humidity was 60%. At the time of treatment, the temperature on the laboratory bench surface where the experiment was conducted was 23.8 C. The treated cover slips were collected at 6, 24, and 48 h and placed in counting vials containing 14 ml of the scintillant. After the vials were thoroughly shaken and allowed to stand for 24 h, the activity in the solutions was radioassayed as described for liquid samples previously.

Statistical treatment. All results were subjected to analyses of variance. The significance of treatment means was determined and, where effects were significant, comparison between means was done using Duncan's multiple range test.

RESULTS AND DISCUSSION

Loss of ^{14}C-fluazifop from a glass surface. Significant losses of ^{14}C-activity occurred from the glass surface during the first 6 h (42% of applied activity) and relatively smaller losses during the next 18 to 42 h (Table 1). By the end of the experiment (48 h after treatment of cover slips) 62% of ^{14}C-activity initially applied had been lost, indicating that loss of ^{14}C-fluazifop due to volatilization from treated plant surfaces probably would be significant.

Table 1. Loss of applied activity of ^{14}C-fluazifop from a glass surface.

Time	^{14}C-activity[a]	Loss of activity
(h)	(dpm/μl)	(%)
0	5130 a	0
6	2986 b	42
24	2147 b	58
48	1968 b	62

[a]Means followed by the same letter are not significantly different at the 5% level using Duncan's multiple range test.

Detached-leaf experiments. Uptake of ^{14}C-activity by quackgrass leaves in the absence of any additional adjuvants is shown in Figure 1. Penetration was measured only up to 24 h due to the use of detached leaves. In this experiment where only 55% of the initial ^{14}C-activity was recovered, by the end of 1 h, 1.4% of the applied activity had entered the leaves. Uptake increased to 3.2% by 6 h and then continued at a slower rate so that by the end of the experiment at 24 h 6.0% of applied ^{14}C-activity had entered the leaf tissue. Foliar uptake with relatively rapid initial penetration, while the herbicide is in the liquid phase, followed by a

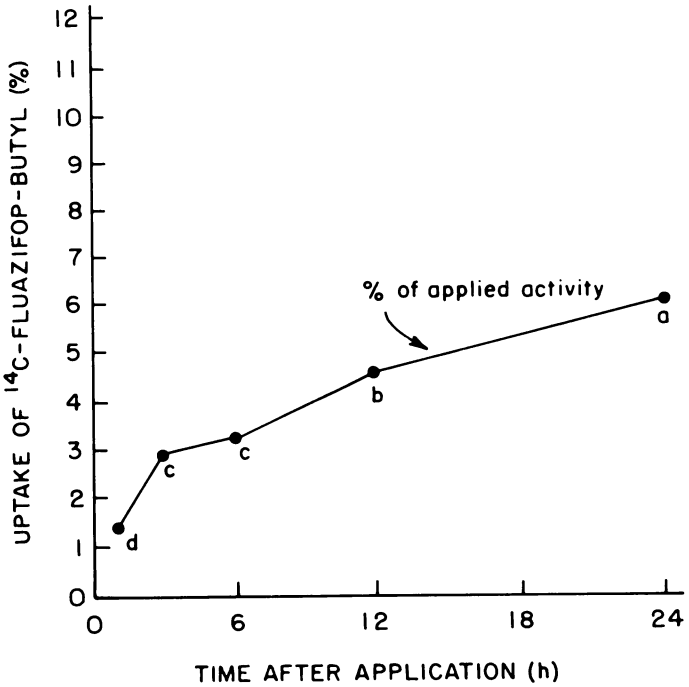

Figure 1. Uptake of ^{14}C-fluazifop by detached leaves of *Agropyron repens*, up to 24 h after application. Values marked by the same letter are not significantly different at 5% level.

[11] Scintillant cocktail containing NE 233 (supplied by Nuclear Enterprises), phenylethylamine (CO_2 absorbent), and ethanol at 1.7:1:1 (v/v/v), respectively.

phase of slow uptake after the droplet has dried, appears to be typical for foliar-applied herbicides (3). However, uptake of ^{14}C-fluazifop by the leaves was relatively low in this experiment. Richard and Slife (18) who had used detached leaves of hemp dogbane (*Apocynum cannabinum* L. # APOCA) to study foliar uptake of ^{14}C-glyphosate [*N*-(phosphonomethyl)glycine] reported considerably less uptake of the herbicide than had been reported by other workers who had used intact plants (9, 12, 14, 19). Without additives, only 1.8% of technical ^{14}C-glyphosate had been absorbed in the first 30 min, with no further increases in the next 7.5 h. They attributed this poor uptake to the apparent lack of a driving force for diffusion across the cuticle in detached leaves, and the same explanation may hold true, at least partly, for our experiment.

In the second detached-leaf experiment which investigated the effect of adjuvants on uptake, the adjuvants increased the absorption of ^{14}C-activity significantly at both harvest times (Table 2). In the herbicide alone treatment, 1.9 and 5.4% of applied activity had entered the leaves by 6 and 24 h, respectively. With 0.2% (v/v) Agral, 17.2% of the applied activity and with 2.0% (v/v) Actipron, 12.9% of applied activity were absorbed by 24 h. At 24 h, the uptake of the radiolabel in the presence of 0.5 or 1.0% (v/v) Actipron was less than with 0.2% (v/v) Agral. This is suggestive of a difference in the way the two adjuvants act. Singh et al. (22) reported that a phytobland oil (2.5% Sun 11E) promoted foliar absorption of ^{14}C-prometryn [*N,N'*-bis(1-methylethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine] by soybean, but only during the early hours of treatment. In contrast to this, a continuous improvement of uptake up to 20 h resulted in the presence of a surfactant (0.5% Multifilm X-77) (22). Our results also suggest that the oil additive may cause more rapid early penetration of the treated leaves, while the surfactant may influence uptake over a longer period of time. Total recovery in this experiment was 66% of the applied activity.

Whole-plant experiments. Recovery of ^{14}C-activity following applications of ^{14}C-fluazifop decreased with time. Only 43% of applied activity could be recovered from the plants after 48 h, and by 168 h this figure was down to 30% (Table 3). Kells et al. (10), investigating uptake of fluazifop by quackgrass and soybeans, also reported that recovery of applied ^{14}C-activity decreased with time after application. Recovery of applied ^{14}C, 144 h after treatment, was 66.2% in quackgrass (10). The plants used in these experiments were much larger than those used by Kells et al. (10). It is possible that some underestimation of recovery of total activity applied may have resulted from the subsampling of large plant parts. The fact that volatilization leads to considerable losses of activity was established in the glass cover slip study. In our opinion, this is one of the major reasons for the inability to recover all of the ^{14}C-activity applied in the whole-plant experiments. Low recoveries of ^{14}C-activity as was encountered in the present studies are not uncommon in the literature on foliar uptake and translocation studies involving both field and glasshouse experiments (2, 19, 21, 23, 24). Sharma and Vanden Born (21), working with ^{14}C-picloram (4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid), recovered only 55, 64, and 75% of the total applied activity from treated plants of barley (*Hordeum vulgare* L.), Canada thistle [*Cirsium arvense* (L.) Scop. # CIRAR], and soybean, respectively, and attributed these losses to volatilization from leaf surfaces and radioactivity lost as $^{14}CO_2$ or exuded by roots. In field-grown common milkweed (*Asclepias syriaca* L. # ASCSY) and hemp dogbane (*Apocynum canabinum* L. # APCCA), Wyrill and Burnside (24) recovered only 17 and 15% of ^{14}C-2,4-D [(2,4-dichlorophenoxy)acetic acid] and 23 and 13% of ^{14}C-glyphosate respectively, 12 days after application. Schultz and Burnside (20) suggested that the activity not accounted for in the previous study (24) may have been lost through: a) leaf wash procedures, b) absorption into the lanolin ring, c) hair roots not recovered from the soil, d) exudation of radiolabeled herbicide or metabolites from roots into the soil, e) $^{14}CO_2$ evolution after metabolism of the herbicide, and f) volatiliza-

Table 2. Effects of surfactant (Agral) and oil additive (Actipron) on uptake of ^{14}C-fluazifop by detached quackgrass leaves, 6 and 24 h after application.

Treatments	Time of harvest (h)[a]	
Fluazifop-butyl + additive	6	24
(%, v/v)	(% of applied)	
+ 0.00 additive	1.9 c	5.4 d
+ 0.05% Agral	3.9 b	10.7 bc
+ 0.1% Agral	7.5 a	11.6 bc
+ 0.2% Agral	8.8 a	17.2 a
+ 0.5% Actipron	10.3 a	9.1 c
+ 1.0% Actipron	3.8 b	10.5 bc
+ 2.0% Actipron	9.8 a	12.9 ab

[a]Means within each column followed by the same letter are not significantly different at the 5% level using Duncan's multiple range test.

Table 3. Recovery, uptake, and translocation of ^{14}C-fluazifop applied to quackgrass plants, without additional adjuvants.

Time	Percent of applied ^{14}C[a]			
	Recovered[b]	Leaf wash	Absorbed	Translocated
(h)	(%)			
12	41.5 ab	25.6 a	15.9 ab	2.0 c
24	33.8 bc	21.2 b	12.4 b	2.2 c
48	42.9 a	26.9 a	16.2 ab	4.9 b
72	30.9 c	16.1 c	14.8 ab	5.1 b
168	30.1 c	11.6 c	18.5 a	6.9 a

[a]Means within each column followed by the same letter are not significantly different at the 5% level using Duncan's multiple range test.

[b]Total activity recovered in the experiment as % of applied.

Table 4. ^{14}C-activity in leaves, stems, roots, rhizomes, and tillers, at various times after application of ^{14}C-fluazifop to quackgrass plants[a].

Assayed portion[a]	Time after application (h)				
	12	24	48	72	168
	(dpm/g)				
Leaves above	0.3 c	0.7 c	2.7 b	1.9 bc	3.9 a
Leaves below	0.4 c	0.9 bc	1.6 b	2.6 ab	4.5 a
Stem above	0.1 c	0.9 c	2.5 b	2.9 ab	3.5 a
Stem below	0.8 b	0.9 b	1.9 a	2.0 a	2.4 a
Tillers	. . .	0.04 b	0.05 b	0.06 ab	0.08 a
Roots	319.6 a	326.1 a	292.2 a	354.4 a	286.2 a
Rhizomes	. . .	89.3 c	264.3 b	164.2 bc	517.5 a
	(% of translocated)				
Leaves above	1.3 b	3.0 b	8.7 a	7.1 a	8.6 a
Leaves below	0.3 c	3.0 b	7.7 a	8.8 a	10.2 a
Stem above	1.3 c	4.2 b	6.0 b	7.9 ab	12.0 a
Stem below	23.2 b	24.8 b	35.7 a	32.2 a	33.2 a
Tillers	. . .	1.1 b	2.1 b	3.7 ab	4.8 a
Roots	73.9 a	59.2 a	30.9 b	36.4 b	20.8 b
Rhizomes	. . .	4.7 c	8.9 b	3.9 c	10.4 a

[a]Means in rows followed by the same letter are not significantly different at the 5% level using Duncan's multiple range test.

tion from the leaf surface. Except for b), it is possible that these reasons might account for the low recovery in the present experiments.

In the time-course experiments, the radioactivity in the leaf washes remained relatively constant up to 48 h and then decreased (Table 3). Absorption remained relatively constant up to 168 h. Translocation increased with time (Table 3). Within 12 h after application, 2.0% of applied activity was detected in areas other than the treated zone of the treated leaf. Translocation then continued between 12 and 168 h after which 6.9% of the total applied activity had left the treated zone (Table 3).

Despite the low recoveries at the later harvests, it was evident that greater quantities of the ^{14}C-label had moved to the leaves and stems both above (acropetal movement) and below (basipetal movement) the treated leaf than at earlier harvests (Table 4). This upward and downward movement is indicative of typical phloem-dependent movement as claimed by previous workers (4, 16). The concentration of ^{14}C-activity (dpm/g) which accumulated in the leaves and stems above and below the treated leaf and the activity in the rhizomes increased with time, suggesting that movement is associated with 'source-sink' relationships of the plant (Table 4).

^{14}C-activity in the roots did not increase with time and ranged between 0.8 and 1.1% of the applied activity over the 7-day period (Table 4). It is likely that much of this activity was in root tips. Recovery of roots was difficult, and failure to recover every small rootlet may have resulted in some underestimation of overall plant uptake and translocation. From 24 h onward, activity in rhizomes increased from 0.1 to 0.5% of applied activity after 168 h (data not presented), suggesting that rhizomes are major sinks. The concentration of ^{14}C-activity in the rhizomes showed an increase of approximately 80% between the harvest times 24 and 168 h (Table 4). The distribution of this ^{14}C-activity along the lengths of rhizomes is shown in Figure 2. After 24 h, all three segments (i.e., apical, basal, and middle pieces) had nearly equal quantities of ^{14}C-activity. As time progressed, the pattern changed and the concentration of ^{14}C-activity in the apical pieces greatly increased. Concentration of activity in the basal and middle pieces tended to decline although the decreases were not statistically significant. Figures 3a and 3b are diagrams of the rhizome systems of single plants illustrating the ^{14}C-distribution in each rhizome system. These profile diagrams also show the accumulation of ^{14}C-fluazifop in the apical regions of rhizomes, while relatively little activity remained in basal and middle areas. The results suggest a flow of herbicide along the rhizome leading to greater accumulation at the apices.

The pattern of accumulation of ^{14}C-fluazifop in quackgrass rhizomes was similar to that described for glyphosate (5, 7, 12). Claus and Behrens (5) found that ^{14}C-glyphosate accumulation was greatest at nodes near the quackgrass rhizome tips and least in nodes near the mother shoot. McIntyre and Hsiao (12) found evidence that accumulation of ^{14}C-glyphosate was greatest in the youngest and most rapidly growing buds at the apical region of quackgrass rhizomes and that activity decreased in successively older buds behind the apex.

In the experiment that investigated the influence of adjuvants on uptake and translocation of ^{14}C-fluazifop, the average recovery of ^{14}C-activity was 31.6% of applied activity after 72 h. Compared with treatments without adjuvants, except in the case of 0.1% (v/v) Agral, the total uptake was significantly higher in treatments with adjuvants (Table 5).

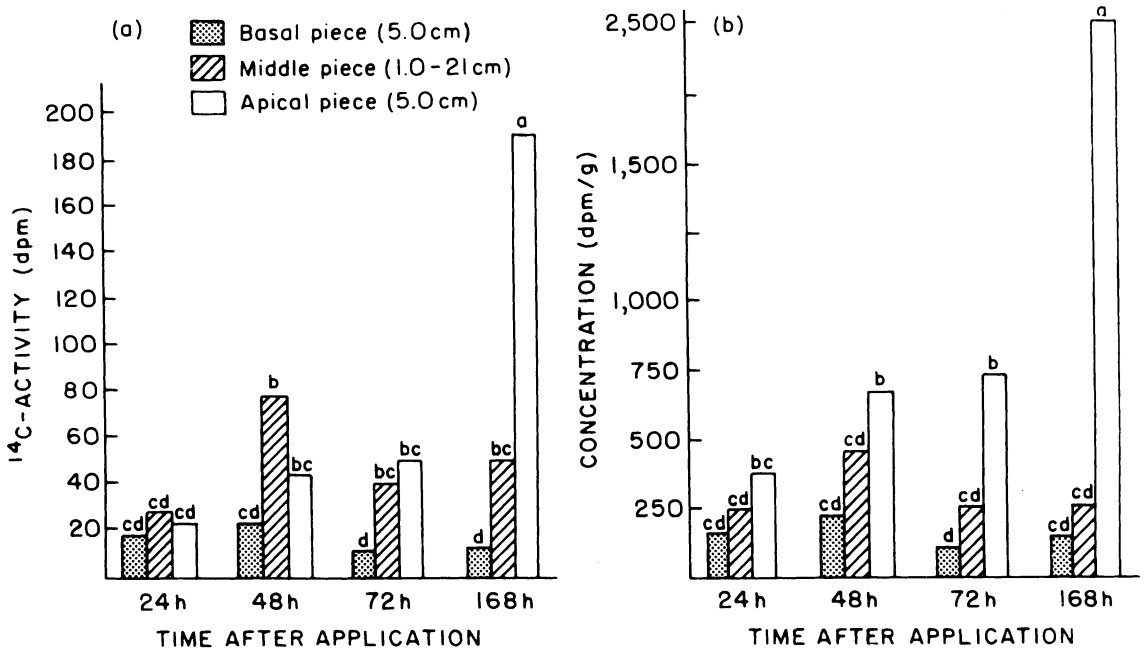

Figure 2. Distribution of ^{14}C-activity (dpm) (a), and concentration (dpm/g) (b) in rhizomes exceeding 10 cm in length. Means of six rhizomes obtained from three replicate plants per harvest time. Bars marked with the same letter are not significantly different at 5% level.

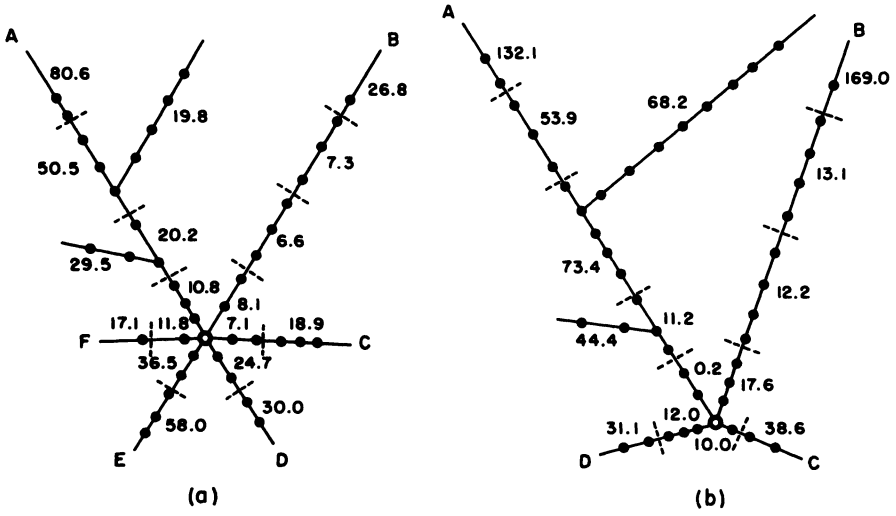

Figure 3. Typical distribution profiles of ^{14}C-activity (dpm) in rhizomes of quackgrass: (a) 48 h, and (b) 168 h after application of ^{14}C-fluazifop to whole plants. The central open circles indicate the position of the treated shoot. Rhizomes are drawn to scale (1.0 cm of rhizome = 2.0 mm in the figure); broken lines across rhizomes show position of fragmentation of pieces for radioassay; dots on rhizomes indicate nodes.

However, Agral at this rate did increase uptake in the detached-leaf experiments (Table 2). Despite increased uptake with adjuvants, a corresponding increase in the activity translocated out of the treated leaf was not found. The difference in total uptake appears to be mainly due to significantly greater amounts of the ^{14}C-label being present in the treated zones, since greater penetration occurred in the presence of adjuvants. The activity distributed in stems and leaves both above and below the treated leaf varied without any clear trend. The activity translocated to roots and rhizomes also did not differ significantly among treatments.

Total recoveries in the experiment on the influence of adjuvant mixtures on ^{14}C-uptake and translocation ranged between 35.2 and 51.6% of the applied activity 72 h after treatment (Table 6). Total uptake was greater in all four treatments with additional adjuvants compared with treat-

Table 5. The effect of surfactant Agral, and oil additive Actipron on uptake, translocation, and recovery of ^{14}C-fluazifop in quackgrass plants, 72 h after treatment.

	Percent of applied ^{14}C[a]				
	Fluazifop + additive[b]				
Wash or tissue fraction	Herbicide alone	AG at 0.1% (v/v)	AG at 0.2% (v/v)	AC at 1.0% (v/v)	AC at 2.0% (v/v)
	(%)				
Leaf wash	32.1 a	27.3 bc	28.6 ab	22.8 cd	21.6 d
Activity in the treated leaf					
Treated zone	0.3 c	0.3 c	2.0 b	4.6 a	2.7 ab
Above treated zone	0.7 b	2.1 a	0.8 b	0.7 a	1.9 a
Below treated zone	0.8 a	0.3 a	0.4 a	0.4 a	0.8 a
Activity in rest of plant					
Leaves and stem above	0.4 ab	0.2 b	0.8 a	0.2 b	0.2 b
Leaves and stem below	0.9 a	0.7 ab	0.7 ab	0.5 c	0.5 c
Roots and rhizomes	0.8 a	0.6 a	0.6 a	0.8 a	0.8 a
Total recovery	35.9 a	31.6 b	34.0 b	29.9 b	28.5 b
Total uptake	3.9 b	4.3 ab	5.4 a	7.2 a	6.9 a
Total translocation	2.1 a	1.6 a	2.2 a	1.5 a	1.5 a

[a]Means within a row followed by the same letter are not significantly different at the 5% level using Duncan's multiple range test.

[b]AG = Agral; AC = Actipron.

Table 6. The effect of several mixtures of Agral and Actipron on uptake, translocation, and recovery of ^{14}C-fluazifop in quackgrass plants, 72 h after treatment.

	Percent of applied ^{14}C[a]				
	Fluazifop + adjuvant mixture[b]				
Wash or tissue fraction	Herbicide alone	AG 0.1%, AC 1.0% (v/v)	AG 0.2%, AC 1.0% (v/v)	AG 0.1%, AC 2.0% (v/v)	AG 0.2%, AC 2.0% (v/v)
	(%)				
Leaf wash	36.8 a	32.8 ab	38.8 a	28.7 b	32.6 ab
Activity in treated leaf					
Treated zone	1.0 b	4.8 a	3.9 a	2.6 a	2.3 a
Above treated zone	0.8 c	6.9 a	7.3 a	3.0 b	2.4 b
Below treated zone	0.4 a	0.7 a	0.4 a	0.3 a	0.5 a
Activity in rest of plant					
Leaves and stem above	0.3 a	0.4 a	0.5 a	0.2 a	0.2 a
Leaves and stem below	0.3 b	1.2 a	0.5 b	0.13 c	0.14 c
Roots and rhizomes	0.06 b	0.3 a	0.3 a	0.2 a	0.24 a
Total recovery	39.6 ab	45.2 ab	51.6 a	35.2 b	38.4 b
Total uptake	2.8 c	14.3 a	12.8 a	6.5 b	5.8 b
Total translocation	0.6 b	1.9 a	1.3 a	0.5 b	0.6 b

[a]Means within a row followed by the same letter are not significantly different at the 5% level using Duncan's multiple range test.

[b]AG = Agral; AC = Actipron.

ments without them. Translocation out of treated leaf was significantly greater in the treatments having 0.1 or 0.2% Agral with 1.0% Actipron, compared with all other treatments. In the presence of adjuvants mixtures, significantly greater amounts of ^{14}C-activity were found in the treated zones and above treated zones in the treated leaves (Table 6), indicating that much of this increased activity taken up was retained in the treated leaves themselves. Acropetal translocation (leaves and stems above treated leaf) showed no significant differences between any of the treatments. However, differences between minus and plus adjuvants (Table 6) show a significant increase in percent radioactivity in the roots and rhizomes (basipetal translocation) in the presence of adjuvant mixtures.

In both of these whole-plant experiments, there was clear evidence that the two adjuvants either alone or in combination increased the uptake of ^{14}C-fluazifop significantly. In both experiments much of the additional recovered activity was found within the treated leaf, with substantial quantities accumulating in areas above the treated zone. Increased foliar uptake and migration of herbicides distally in the treated leaves in the presence of adjuvants have also been reported previously. Barrentine and Warren (1) reported a fourfold and eightfold increase in the penetration and acropetal movement within treated leaves of chlorpropham (1-methylethyl-3-chlorphenylcarbamate) in giant foxtail (*Setaria faberii* Hermm. # SETFA) and ivyleaf morningglory [*Ipomoea hederacea* (L.) Jacq. # IPOHE], respectively, in the presence of isoparaffinic oil additive. Coats and Foy (6) also reported that paraffinic and naphthenic phytobland oils markedly enhanced foliar uptake and acropetal translocation of ^{14}C-atrazine, [6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine] to distal areas of the treated leaves of corn (*Zea mays* L.).

No attempt was made in the present studies to establish whether the radioactivity measured was due to the ^{14}C-fluazifop molecule or one of its major metabolites. Further studies would be necessary to ascertain whether the molecule is metabolized once it enters the plant. Quantitative comparisons of the degree of mobility of fluazifop with other herbicides having systemic activity is difficult due to the low recoveries of applied ^{14}C-activity in the present studies. Future studies will need to establish whether this may have been due to the inherent volatility of fluazifop or some other cause. Usage of somewhat smaller plants and a higher dose of radioactivity might be helpful in future studies.

ACKNOWLEDGMENTS

The authors are grateful to the Plant Protection Division of the I.C.I. (U.K.) for supplying samples of the ester of fluazifop. Thanks are extended to Mr. Gareth Williams for technical assistance, Drs. C. Marshall and R. C. Kirkwood for valuable advice during preparation of the manuscript, and to the Commonwealth Scholarships Commission (U.K.) for a scholarship to the senior author.

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Weed Science. 1986. Volume 34:684–688

Inhibited Mitotic Entry is the Cause of Growth Inhibition by Cinmethylin[1]

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Abstract. **The herbicide cinmethylin {*exo*-1-methyl-4-(1-methylethyl)-2-[(2-methylphenyl)methoxy]-7-oxabicyclo [2.2.1]heptane} inhibited oat (*Avena sativa* L. 'Porter') root growth during the first 6 h of treatment at a concentration of 6.7×10^{-8}M. A concentration of 1×10^{-8}M cinmethylin inhibited root growth within 12 to 18 h. Inhibition of shoot growth was less sensitive, but was inhibited by 36 to 48 h after treatment with 1×10^{-7}M and by 12 to 24 h after treatment with 1×10^{-5}M cinmethylin. Cinmethylin concentrations of 1×10^{-5}M and lower did not inhibit cell elongation in isolated oat coleoptiles during a 24-h exposure. Mitotic frequency in oat root tips was reduced after 12 h of treatment with 1×10^{-7}M cinmethylin. The frequency of all stages of mitosis (prophase, metaphase, and anaphase + telophase) was reduced. Concentrations of 1×10^{-6}M cinmethylin resulted in nearly complete arrest (87% inhibition) of mitosis. These data suggest cinmethylin inhibits growth by inhibiting entry of cells into mitosis. The cause of mitotic arrest is unknown; however, the mechanism appears to be different from other herbicides known to inhibit mitosis.**

Additional index words. **Cell enlargement, cell division, mitosis,** *Avena sativa* **L.**

INTRODUCTION

Cinmethylin is a cineole herbicide being developed by the Shell Development Company. This herbicide has shown promise as a soil-applied treatment to provide excellent grass and moderate broadleaf weed suppression for 4 to 8 weeks in soybeans [*Glycine max* (L.) Merr.], cotton (*Gossypium hirsutum* L.), and peanuts (*Arachis hypogaea* L.) (10). Since this compound represents a totally new herbicide class, no studies have been published on its mode of action. From preliminary studies, the mode of action appears to be inhibition of growth in roots and shoots of susceptible plants (9). No other symptomatology has been reported for this herbicide; thus growth inhibition appears to be its primary mode of action.

Plant growth can be defined as an irreversible increase in size resulting from the processes of cell division and cell enlargement (5). A herbicide can influence growth by affecting either or both of these processes, and the most common herbicide site of action for growth inhibition is the shoot tip and root tip meristem. Plant meristems are composed of cell populations actively progressing through the cell cycle, which consists of four stages: G_1 (Gap_1), S (Synthesis), G_2 (Gap_2), and M (Mitosis) (7). Mitosis is subdivided into four stages: prophase, metaphase, anaphase, and telophase. Reviewing the metabolic effects influencing mitosis, Rost (16) reported that each of these stages requires certain specific enzymes, proteins, and RNAs in order to progress to the next cell cycle stage. Also, all of the events require a constant source of oxygen, a certain level of hydration, a carbon source, and energy metabolism (ATP synthesis and utilization) (16). Inhibition of any of these requirements will affect the cell cycle.

To define the type of cell cycle aberration occurring, the most common procedure is to categorize the cells in a root tip meristem into interphase, prophase, metaphase, anaphase plus telophase, or aberrant (5). Changes in the frequency of these stages, in relation to nontreated roots, can reveal significant information with respect to herbicide site of action in the cell cycle sequence. When cell cycle

[1] Received for publication November 12, 1985, and in revised form March 26, 1986. Purdue Agric. Exp. Stn. J. Art. No. 10536.

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